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Final Technical Report

NASA Cooperative Agreement NCC2-874

"TRANSIT OF EXTRASOLAR PLANETS"

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by

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Final Report on NCC 2-874: Transit of Extrasolar Planets

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During the past five years we have pursued the detection of extrasolar planets by the photometric transit method, i.e. the detection of a planet by watching for a drop in the brightness of the light as it crosses in front of a star. The planetary orbit must cross the line-of-sight and so most systems will not be lined up for such a transit to ever occur. However, we have looked at eclipsing binary systems which are already edge-on. Such systems must be very small in size as this makes the differential light change due to a transit much greater for a given planet size (the brightness difference will be proportional to the area of the transiting planet to the disc area of the star). Also, the planet forming region should be closer to the star as small stars are generally less luminous (that is, if the same thermal regime for planet formation applies as in the solar system). This led to studies of the habitable zone around other stars, as well. Finally, we discovered that our data could be used to detect giant planets without transits as we had been carefully timing the eclipses of the stars (using a GPS antenna for time) and this will drift by being offset by any giant planets orbiting around the system, as well.

The best summary of our work may be to just summarize the 21 refereed papers produced during the time of this grant. This will be done in chronological order and in each section separately.

Detection of Extrasolar Planets (papers 1-12)

Paper 12 by Hale and Doyle is essentially a catalogue of the space orientation of stars determined by using their Calcium II H & K-line emission to get the periods of rotation (P) of each star. From the rotational velocity ($V \sin i$, where V = rotational velocity and i = rotational axis inclination from the line-of-sight) and the circumference of the star of radius R , one can get the star's inclination toward or away from the observer using $2\pi R / P = V$, and $V \sin i / V = \sin i$. Dr. Hale and I obtained a list of likely edge-on systems in this way in which the photometric method could be applied. Incidentally, every system around which planets have been discovered since has been contained in our catalogue list of likely candidates.

Paper 11 by Schneider and Doyle outlines a roadmap for the transit detection of Earth-like planets around some very special small-mass eclipsing binaries. In this work we show that precessional damping will occur within the protoplanetary disc so that as planets form they should collisionally damp into the binary orbital plane. Example systems to be observed, and possible follow-up observations to detect exobiology are also outlined. This paper announced the organization of the TEP (Transit of Extrasolar Planets) observing network, with participating observatories in California, Korea, Russia, Crete, France, Canary Islands, New York, and New Mexico, which the authors organized.

Paper 10 of Brandmeier and Doyle is the first paper showing the quasi-periodicity of planetary transits around eclipsing binary stars. This led to the development of a transit detection algorithm to cross correlate all possible transit models that could take place around eclipsing binary stars of a given type (varying phase and periods of the planets and stars).

Paper 9 by Jenkins, Doyle, and Cullers is the actual transit detection algorithm developed along the lines of signal detection theory. We had preliminarily characterized the observational noise as white and Gaussian (WGN) but later found it to be a bit red. Nevertheless, in this paper we showed that Earth-sized planets could indeed be detected using ground-based 1-meter-class telescopes photometrically.

Paper 8 by Doyle et al. reported on the actual characteristics of observational data taken at the University of California's Lick Observatory Crossley 0.9-meter reflector. At his time we had hundreds of hours of observing time and were able to characterize the noise well, and place limits on extrasolar planets around the smallest star in our sample, CM Drac, of sizes a bit smaller than Neptune (which is about the detection limit of most other systems). We also here pointed out that giant planets could be detected without transits just by GPS timing eclipses of the binary stars well.

Paper 7 is a semi-technical article aimed at the advanced amateur astronomy community to point out to them that with 1% photometric CCD capabilities and a GPS timing chip in their data acquisition computers, they could participate in the detection of jovian mass planets.

Paper 6 is a report by one of the TEP network observatories on multicolor photometry and flare activity of CM Draconis (one of the many astrophysical asides of the data when looking for extrasolar planets).

Paper 5 is a report from the Canary Islands node of the TEP Network regarding the characterization of our data reduction software and processes. As part of the effort, we invented new aperture photometry software tools that have been incorporated into the National Optical Astronomy Observatory's IRAF image processing package and is available on the TEP Network web site.

Paper 4 outlines the process and procedure of calibrating and reducing multi-site photometry and integrating it into one common light curve. We rejected all data that was of a precision worse than about 0.8%.

Paper 3 is a demonstration of the jovian planets detection method along with data obtained at Lick Observatory and the Canary Islands Observatory for about 15 small mass eclipsing binaries. In this article we put limits on the presence of any jovian-to-brown-dwarf masses around these stars.

Paper 2 is a 5-year report on the 1000+ hours of observations taken to date by the TEP network including a full description of the data, its noise characteristics, the observatories, telescopes, and phase coverage of possible planets these observations have achieved to date.

Paper 1 is a final report (if not funding is obtained) on the CM Drac Earth-like planets detection limits we have reached. It shows that Earth-like planets can indeed be detected from the ground using 1-meter-class telescopes around selected stars. The limit we report here is for 3-Earth Radii planets being detectable at the 90% confidence level (this is a planet 2% the size of Jupiter!)

Circumstellar Habitable Zones [papers 13-19]

Paper 19 outlines a theory to explain how liquid water could have existed on early Mars, while also necessarily addressing the problem of the solar lithium depletion, excess heavy element abundances in older lunar soils, and Venus' early ocean loss. We proposed that the early Sun could have been 3-7% more massive.

Paper 18 addresses the stellar considerations of the history of the young Solar System, specifically showing that if young solar-type stars lose a small percentage of their masses this can be detected at radio wavelengths.

Paper 17 argues that the best solution to liquid water on early Mars might be early solar mass loss as the idea of condensation of greenhouse gasses due to the early dimmer Sun as well as substitution of other atmospheric greenhouse constituents is not viable as an explanation of liquid water on early Mars.

Paper 16 reports VLA multispectral radio observations of young solar type stars with limits on their possible mass loss rate. While this study was not conclusive as yet, it demonstrated that such radio observations are indeed capable of detecting such a mass loss rate and so could confirm if, in general, young solar-type stars do have slightly more mass when young compared to their later main-sequence lifetimes. This would have significant repercussions for our understanding of the history of the Solar System, including the origin of biological systems.

Paper 15 is 533-page 62-author volume which we refereed and edited. It is the result of a conference we organized and held at NASA Ames Research Center in Moffett Field, California.

Paper 14 is a review article over viewing the current state of the field of Circumstellar Habitable Zones, with updates in many of the related multi-disciplinary fields.

Paper 13 is an article addressing the problem of complex photosynthetic biological habitability around M-stars (i.e. stars in which the peak flux is in the infrared and any planets in the habitable zone will be tidally locked in rotation). We are, as far as we know, the first to address this interesting problem; of some significance since as much as 75% of stars may be M-spectral-type dwarfs stars.

Peripherally related work [papers 20-21]

Paper 21 reviews all the work done on archaeoastronomy in sub-Saharan Africa. As this grant has not been fully funded, as a part time job, the author taught History of Science as a visiting professor at Principia College in Illinois, and this paper is the result of some of that research, as well as two expeditions to Africa he led at an earlier time with Mr. Frank.

Paper 20 introduces a new tool for objectively intercomparing various species vocalizations. It does this by using Information Theory statistics (originally developed for telephone line capacity measures) to the analysis of dolphin whistle vocalizations, also showing their applicability to other diverse species.

One can see that many basic scientific breakthroughs in various field have been made through this agreement over the past five years. An average of over 4 refereed paper per year during this time demonstrates our productivity. Given that during this time period two NASA Ames Research Center Director's Discretionary Funds (\$40K per year for two years) and a special \$5K grant were our only sources of funding, this might be viewed as particularly remarkable.

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